



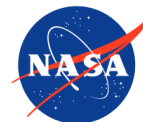
IEEE Aerospace Conference: Big Sky, MT

NEXT-GENERATION RADIOISOTOPE THERMOELECTRIC GENERATOR STUDY

Christopher Matthes, David Woerner, Terry Hendricks, Jean-Pierre Fleurial,
Knut Oxnevad, Chadwick Barklay, June Zakrajsek

Pre-decisional information for planning and discussion only

© 2018 California Institute of Technology. Government sponsorship acknowledged.



Jet Propulsion Laboratory
California Institute of Technology

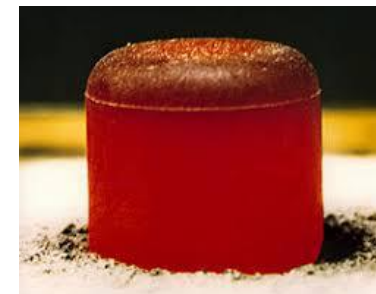
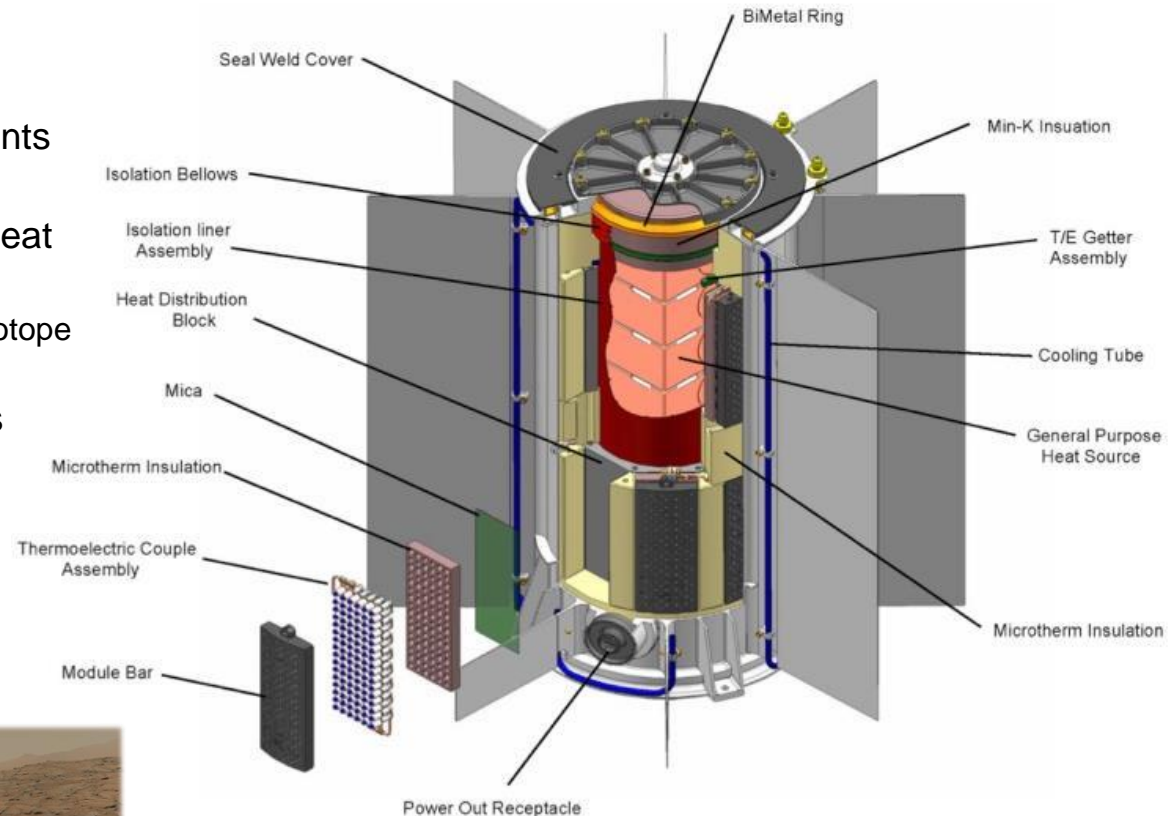
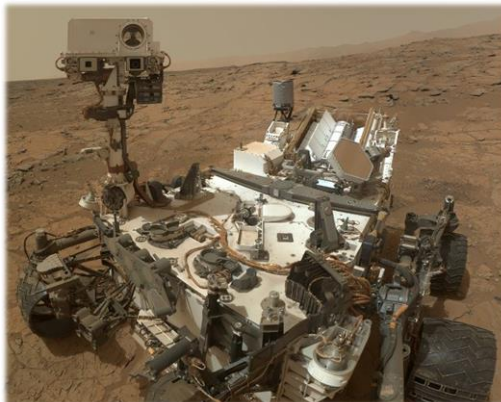
Agenda

- Background
 - Objectives
 - Requirements
 - Study approach
- Thermoelectric Technology
 - Techniques & selection
- RTG Concepts
 - Design considerations
- Roadmap & Summary



What is a Radioisotope Power System (RPS)?

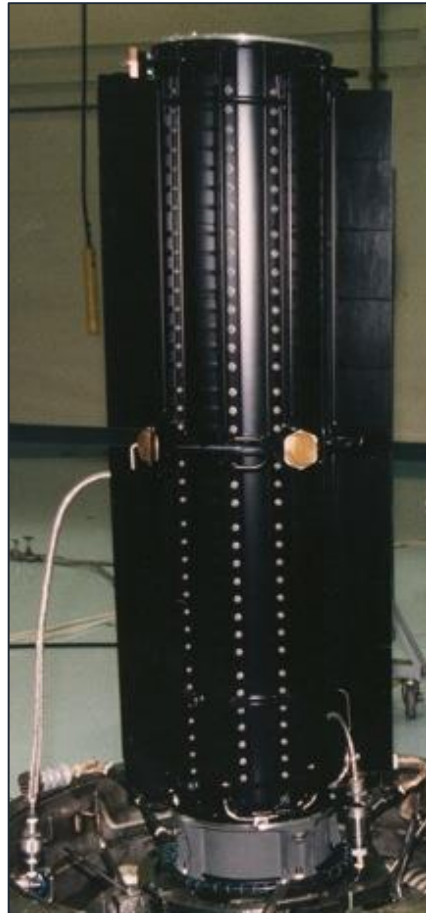
- Provides electricity to missions in remote and challenging environments where solar power is unavailable
- Thermoelectric materials convert heat from a radioisotope into electricity
 - Heat is the natural byproduct of isotope decay
- Used by NASA missions of various types for over 50 years
 - Voyager
 - Galileo
 - Ulysses
 - Cassini
 - Curiosity



Flight Systems for Recent Missions



Multi-Hundred Watt –
Radioisotope Thermoelectric
Generator (MHW-RTG)
(Voyager)



General Purpose Heat Source –
Radioisotope Thermoelectric
Generator (GP-RTG)
(Galileo, Ulysses, Cassini)



Current RPS:
Multi-Mission Radioisotope
Thermoelectric Generator
(MMRTG)
(Curiosity)



Next-Generation RTG Study Objectives

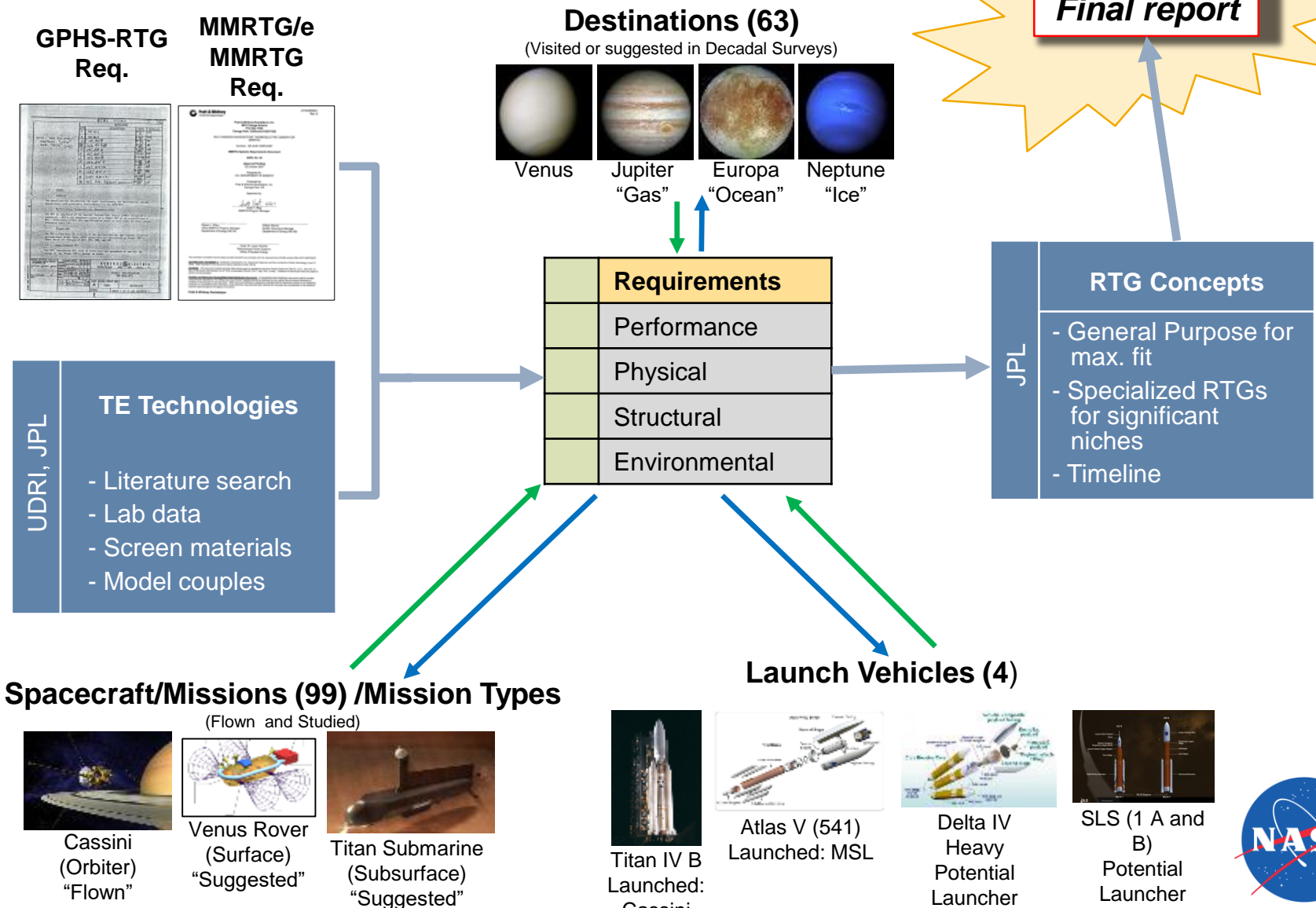
Determine the characteristics of a **Next-Generation RTG** that would “best” fulfill Planetary Science Division (PSD) mission needs.

“**Best**” is defined as a confluence of the following factors:

- An RTG that would be useful **across the solar system**
- An RTG that **maximizes the types** of potential missions: flyby, orbiter, lander, rover, boats, submersibles, balloons
- An RTG that has reasonable development **risks and timeline**
- An RTG that has critical value (**importance, worth, usefulness, performance enhancement**) returned to PSD that warrants the investment as compared with retaining existing baseline systems



Approach For The Study

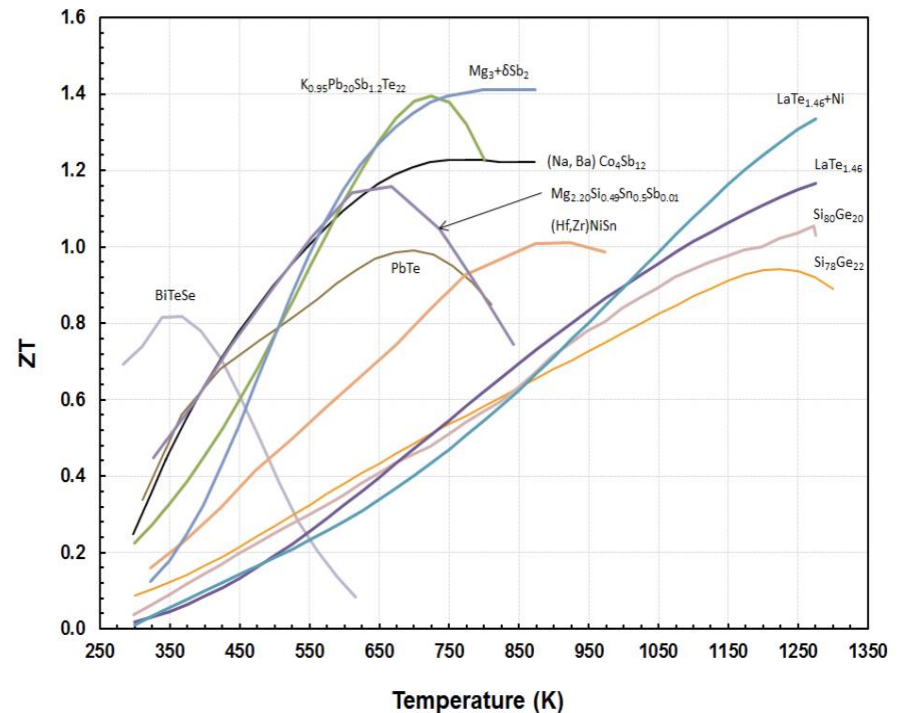


Thermoelectric Technology

- The figure of merit is a dimensionless quantity that characterizes the efficiency of a TE material to convert heat into electrical power

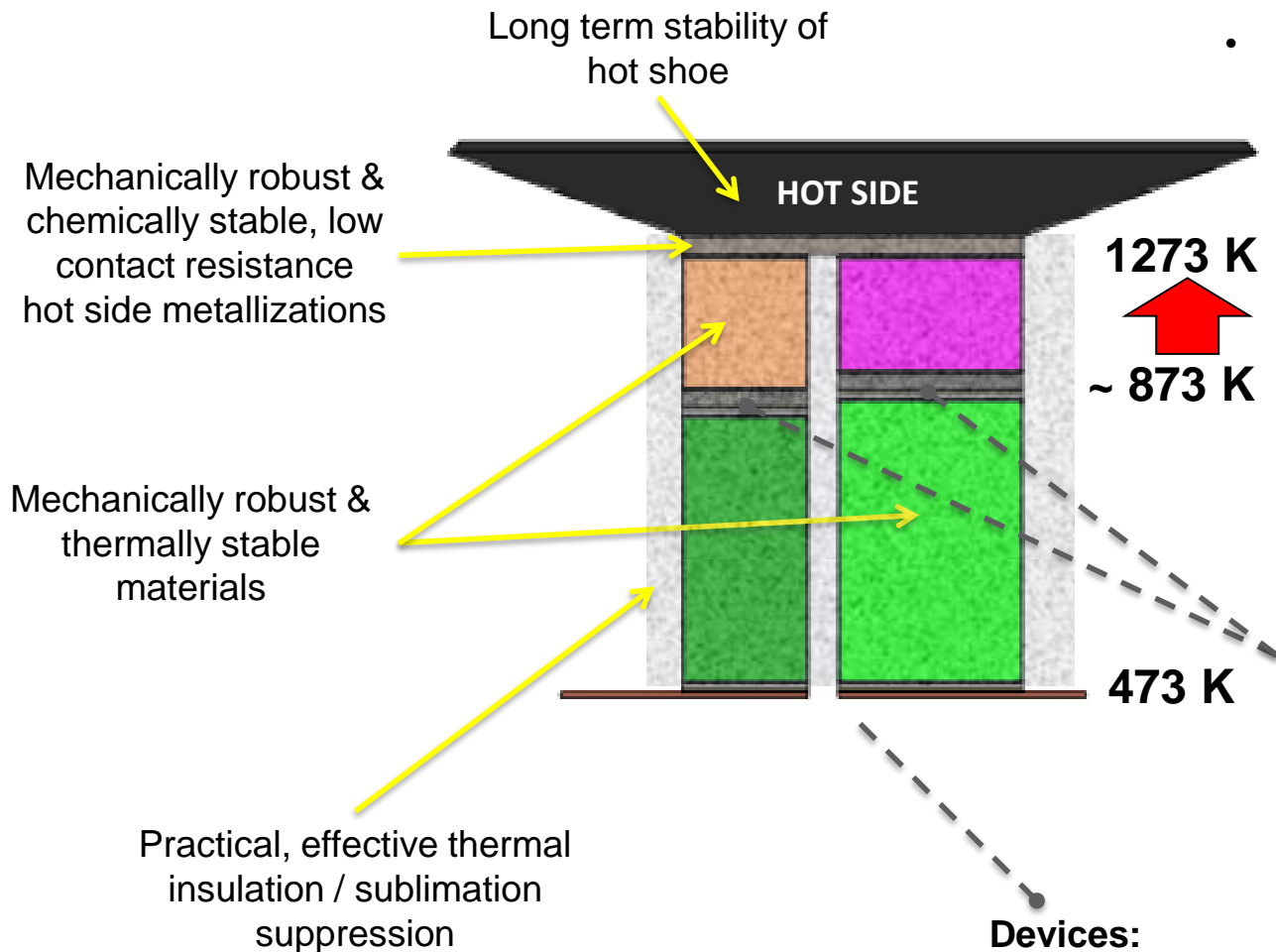
$$ZT = \frac{\alpha^2 T}{\rho k}$$

- α is the Seebeck coefficient,
 - ρ is the electrical resistivity,
 - k is the thermal conductivity
- Segmentation allows for maximization of ZT across temperature range of the couple
 - Segmentation increases risk due to potential for CTE mismatch, interface degradation, material diffusion
- From the candidate materials, a total of 21 optimized couple configurations were conceived for further consideration, and arbitrarily named “TC-1” through “TC-21”
 - This set was reduced to eight for further NASA technology development
 - Selections were TC-1, TC-2, TC-3, TC-4, TC-10, TC-11, TC-14, and TC-21



Thermoelectric Technology

Device Technologies



Materials

- **Advanced complex materials**
 - Zintl, $\text{La}_{3-x}\text{Te}_4$, Bi_2Te_3 and PbTe-based advanced materials
 - Skutterudites

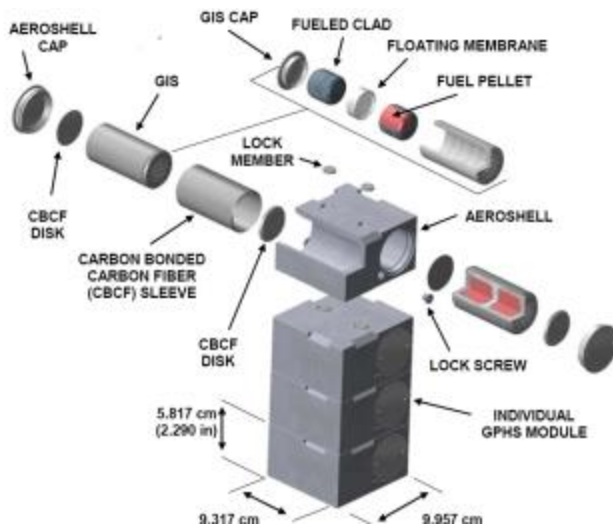
Mechanically compliant, high electrical/thermal conduction segment interfaces

Devices:
Design, Performance testing and modeling

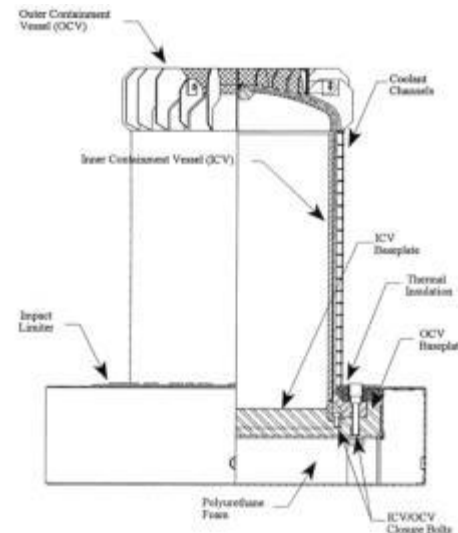


Architectural Trades & Design Constraints

Architectural Trades	Motivation
Couple Segmentation	Maximize couple performance
Cold Systems	Optimize for thermally sensitive environments, and variable thermal environments between different missions
Modular Systems	Optimize radioisotope consumption, ease of spacecraft integration, and closely match power available with power needs
Hybrid Systems	Maximize utility across the solar system and missions



GPHS module



DOE Shipping Cask 9904. Usable internal dimensions: 81 cm in diameter by 135 cm in height.



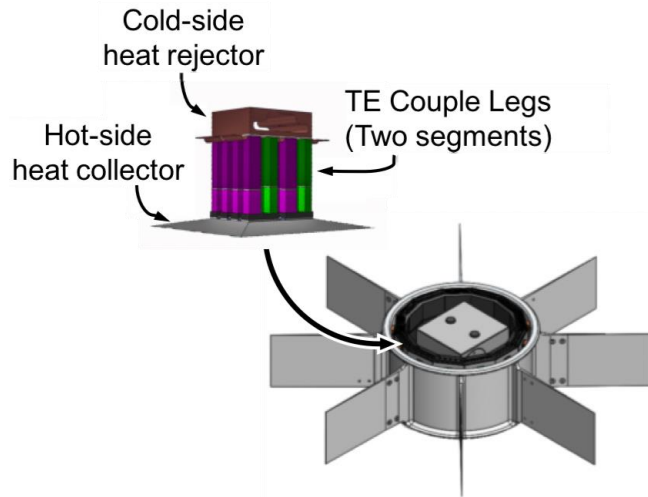
Design Trades

Prefix	Definition	Description
S	Segmented	An SRTG concept would use segmented TECs to boost power and would be a single size, in this case one built around 16 GPHS. No system-level modularity. Optimized for specific power. Operates only in vacuum.
SM	Segmented-Modular	An SMRTG concept uses segmented TECs built into housings that could be procured in differing sizes and hence was modularized at the system level. The size of the variant conceived of in this study was based upon the smallest sized RTG using 2 GPHS. <i>RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible.</i> Operates only in vacuum.
CS	Cold-Segmented	A CSRTG concept designed to the cold-side of the RTG operated at significantly colder temperatures than is typical. This single-sized RTG would be built around 16 GPHS. No system-level modularity. Optimized for specific power. Operates only in vacuum.
CSM	Cold-Segmented-Modular	This generator concept uses the same couples as the SMRTG except that BiTe segments have been added to boost power and lower the cold-side operating temperature. The size of the variant conceived of in this study was based upon the smallest sized RTG using 2 GPHS. <i>RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible.</i> Operates only in vacuum.
HSM	Hybrid-Segmented Modular	This HSMRTG would use segmented TECs in a sealed and evacuated vessel and modularize the system. The size of the variant conceived of in this study was based upon the smallest sized RTG using 2 GPHS. <i>RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible.</i> Operates in vacuum and atmospheres.
CHSM	Cold-Hybrid, Segmented-Modular	Combines the HSMRTG with a segmented TEC whose segments were designed to allow the generator to operate at significantly lower cold-side temperatures. Operates in vacuum and atmospheres. <i>RTGs built around 2, 4, 6, 8, 10, 12, 14, and 16 GPHSs would be possible.</i>

RTG Type/Acronym	Segmented (TECs)	Modular (at the system-level)	Cold (lower cold-side temperature)	Hybrid (vacuum & atmospheres)
SRTG	X			
SMRTG	X	X		
CSRTG	X		X	
CSMRTG	X	X	X	
HSMRTG	X	X		X
CHSMRTG	X	X	X	X

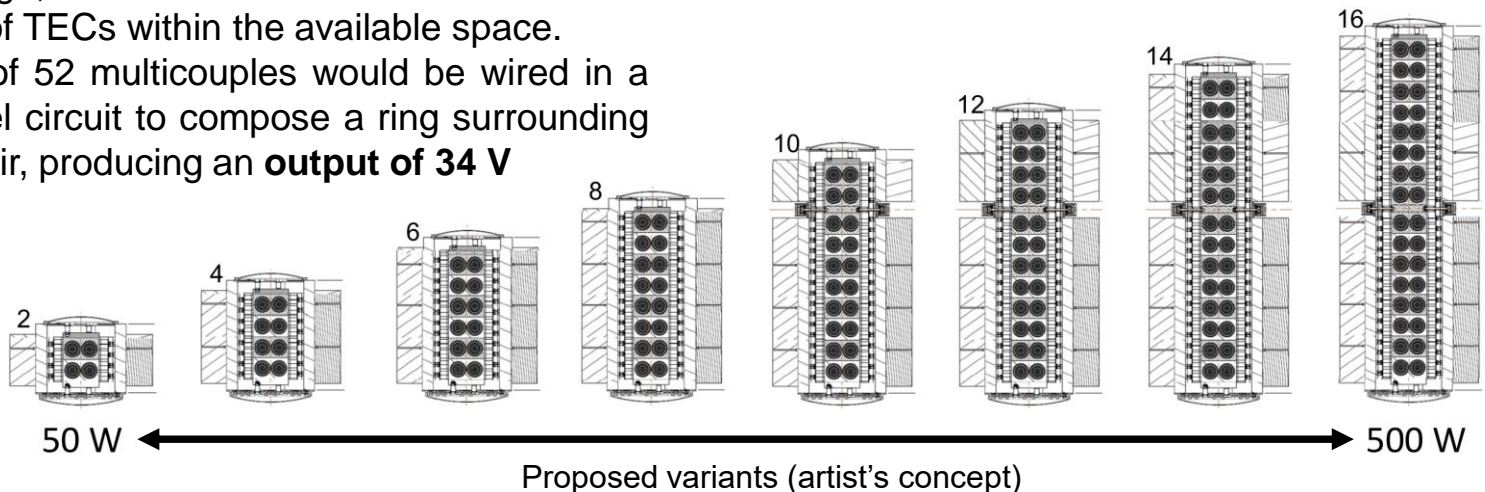


Modularity



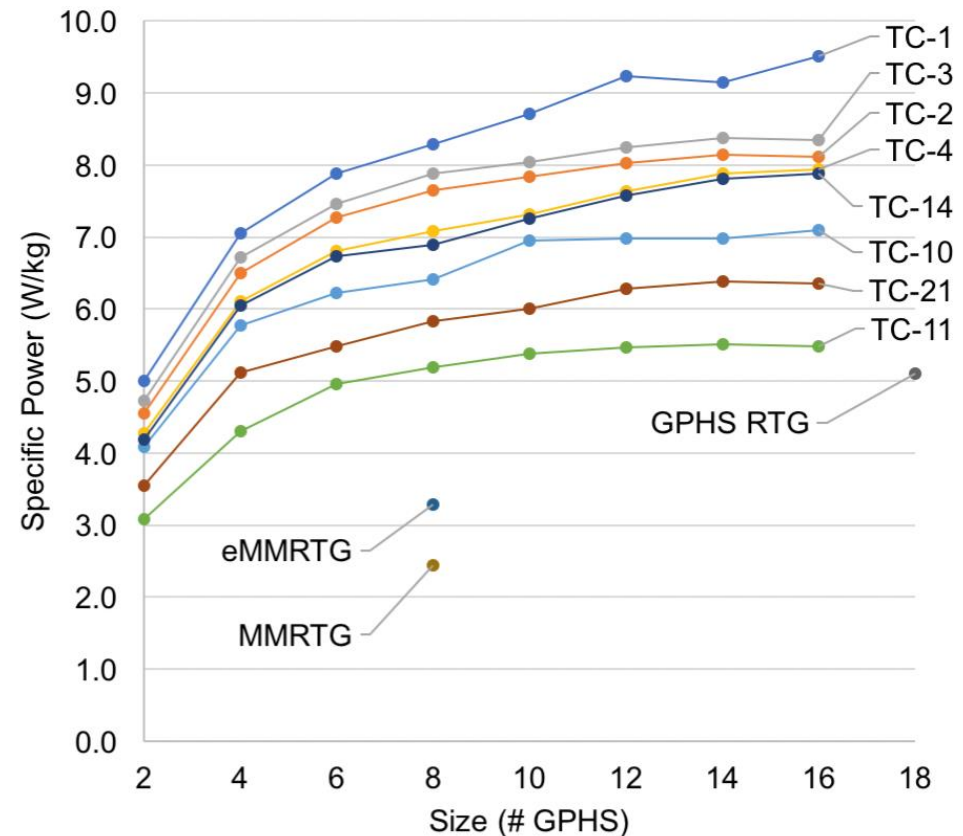
- Typically, NASA spacecraft power busses have been designed to operate in the range of **22 to 36 V**.
- For TECs electrically configured in series, the voltage will be proportional to the number of couples in the circuit.
- A two-GPHS unit was determined to be the **smallest SMRTG variant** capable of supporting the necessary number of TECs to meet the specified voltage requirement.
- This basic architecture would be electrically **integrated in parallel** for larger variants, such that the smallest (two-GPHS) variant determines the output voltage.

- **Multicouples**, a collection of eight TECs within a single package, are used as a means to increase the quantity of TECs within the available space.
- A collection of 52 multicouples would be wired in a series-parallel circuit to compose a ring surrounding the GPHS pair, producing an **output of 34 V**

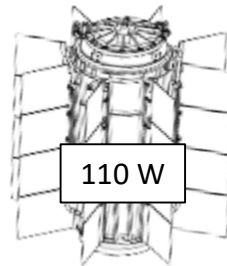


Specific Power

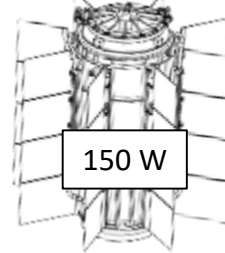
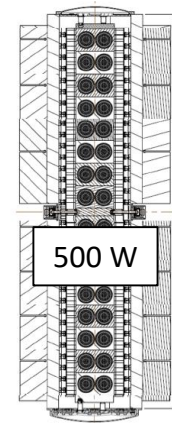
- Figure displays the **BOL specific power** estimates, in W/kg , for the various size options of each TEC selection.
- Nearly all options exceed the specific power of both the MMRTG and eMMRTG
- In some cases the power output using four GPHS may exceed that of the GPHS-RTG using 18 GPHS, resulting in a 78% fuel savings.
- The greater power output of the larger size configurations may eliminate the need for multiple RTGs on certain missions, saving significant mass and fuel resources.
- The specific power of the generator increases with the number of GPHS used, demonstrating that a single larger RTG is more mass efficient than multiple smaller RTGs cumulatively achieving a comparable power level.



RTG Comparison

MMRTG (*Curiosity*,
Dragonfly, *Mars 2020*)

eMMRTG

GPHS RTG
(*Cassini*)Next-Generation
RTG Concept,
16-GPHS version

Power, launch, W	110	150	290 (880)	500
Power, end of life, W	55	91	213 (640)	362
Degradation rate, average	4.8%	2.5%	1.9%	1.9%
Design Life, years	17	17	18	17
# GPHSs	8	8	18	16
Length, m	0.69	0.69	1.14	1.04
Mass, kg	45	44	57	62

Largest variant would be expected to have higher maximum power output, more efficient use of fuel, and a low degradation rate compared with previous RTGs



Roadmap

- Next-Generation RTG design decisions:
 - Vacuum-only
 - Modular
 - 16 GPHSs (largest RTG variant)
 - $P_{\text{BOM}} = 400\text{-}500 \text{ W}_e$ (largest RTG variant)
 - Mass goal of $< 60 \text{ kg}$ (largest RTG variant)
 - Degradation rate $< 1.9 \%$ per yr on average and including fuel degradation
 - System designed to be upgraded with new TC's as technology matures
- Next steps:
 1. Increasing the readiness of the four selected potential TE couple configurations
 2. Procurements to engage industry for the systems design, component technologies, and TE technology





Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

This work was carried out at the Jet Propulsion Laboratory,
California Institute of Technology, under a contract to the
National Aeronautics and Space Administration.